EDGEWOOD
RESEARCH, DEVELOPMENT & ENGINEERING CENTER.

U.S. ARMY CHEMICAL AND BIOLOGICAL DEFENSE COMMAND

AD-A284 313

ERDEC-TR-169

DESIGN OF SPHERICAL AEROSOL PARTICLES
TO MAXIMIZE SOUND ATTENUATION

Janon F. Embury

DTIC
SELECTED
SEP. 13, 1994
S B D

RESEARCH AND TECHNOLOGY DIRECTORATE

June 1994

Approved for public release; distribution is unlimited.

94-29704

DTIC QUALITY INSPECTED 5

Aberdeen Proving Ground, MD 21010-5423

Disclaimer

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorizing documents.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 1994 June	3. REPORT TYPE AND DATES COVERED Final, 93 Jul - 93 Oct

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Design of Spherical Aerosol Particles to Maximize Sound Attenuation	PR-1O162622A552

6. AUTHOR(S)

Embury, Janon F.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
DIR, ERDEC, ATTN: SCBRD-RTB, APG, MD 21010-5423	ERDEC-TR-169

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release; distribution is unlimited.	

13. ABSTRACT (Maximum 200 words)

Analytic expressions for the audible sound absorption and scatter cross sections of an aerosol consisting of spherical particles are identified. The acoustic cross sections per aerosol mass and volume are explored as functions of three independent variables (sound frequency, particle diameter, and particle density) to determine regions of strong attenuation of audible sound. Optimum diameters, and densities that maximize cross sections per mass and volume at specific frequencies are found by reading contour plots contained in the figures of this report. Corresponding expected levels of acoustic attenuation are also contemplated. To a small extent, it is possible to scatter audible acoustic radiation with aerosol particles while aerosol absorption of sound can be significant. Comparing the levels of audible sound attenuation by atmospheric gases plus water vapor with the levels of attenuation achievable with an aerosol, we find that aerosol absorption of sound can greatly exceed that of the intervening air.

14. SUBJECT TERMS Aerosol Particle design	Sound attenuation Acoustic cross sections	Acoustic absorption Acoustic scatter	15. NUMBER OF PAGES 21
			16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-1C.

Blank

PREFACE

The work described in this report was authorized under Project No. 1O162622A552, Smoke/Obscurants. This work was started in July 1993 and completed in October 1993.

The use of trade names or manufacturers' names in this report does not constitute an official endorsement of any commercial products. This report may not be cited for purposes of advertisement.

This report has been approved for release to the public. Registered users should request additional copies from the Defense Technical Information Center; unregistered users should direct such requests to the National Technical Information Service.

Accession For	
NTIS GRA&I	☑
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A	

Blank

iv

CONTENTS

LIST OF FIGURES

Design of Spherical Aerosol Particles to Maximize Sound Attenuation

Introduction

This study investigates the design of aerosols to maximize their acoustic absorption cross section per aerosol mass or volume over the audible frequency range 20-15000 hertz. Air molecules, including water vapor will absorb audible frequencies with little scatter because of their molecular size. To a small extent it is possible to scatter audible acoustic radiation with aerosol particles while aerosol absorption of sound can be significant.

Theory of Attenuation of Sound by Aerosols

In addition to the inverse distance squared drop in sound intensity as acoustic radiation propagates away from the source, we observe attenuation due to absorption by air molecules as indicated by the figures [1] 1 and 2 . Attenuation as a function of relative humidity, temperature, and frequency of sound is indicated in units of m^{-1} and dB/m. These units are related by $m^{-1} = 4.35 \, dB/m$. If an aerosol is present it will scatter and absorb sound with the scatter coefficient concentration product $\alpha_S C$ in units of reciprocal length given by the expression [2]

$$\alpha_S C = \frac{7\pi(2\pi)\left[\dfrac{D}{2}\right]^6 n}{9\lambda^4}$$

where λ is the wavelength of sound, D is the aerosol particle diameter and $n = \dfrac{C_M}{\rho_p \dfrac{\pi}{6} D^3}$ is the number concentration of particles where C_M is the mass concentration and ρ_p the particle density. Because the ratio D^6/λ^4 is so small even for the largest aerosol particles ($D \approx 2 \times 10^{-3}$ cm and the highest frequency of audible sound $\lambda \approx 2$ cm) that at the upper concentration limit set by coagulation $\approx 10^6/cm^3$ the aerosol scatter remains negligible compared to absorption which will now be described.

Absorption of sound by an aerosol occurs as the result of two mechanisms - viscous losses and irreversible heat transfer losses. The viscous losses take place when the aerosol particles move with respect to the air surrounding the particle and the irreversible heat transfer losses take place when heat is transferred between an aerosol particle and the surrounding air. As sound propagates through an aerosol cloud the pressure waves propagate at about 340 m/s at standard temperature and pressure and accelerate particles to oscillate with the air that moves back and forth first in the direction of propagation and then opposite to that direction with the pressure gradient. As air pressure is increased, heat flows from the air into the aerosol particles and when air pressure decreases heat flows from the particles back into the air.

1

The absorption coefficient concentration product representing viscous losses may be written [3,4]

$$\alpha_a^\nu C = \frac{3\pi\nu Dn}{U_S}\left[1 + \frac{1}{\beta}\right]\mu_\nu$$

where $\nu \approx .15\ cm^2/s$ is the viscosity of air, $U_S \approx 340m/s$ is the speed of sound, D is the particle diameter, n is the aerosol particle number concentration defined earlier,

$$\beta = \frac{2}{D}\left[\frac{2\nu}{\omega}\right]^{1/2}$$

where ω is the angular frequency and

$$\mu_\nu = \frac{\left[\dfrac{2\rho_p}{3\rho_{air}}\right]^2}{\left[\dfrac{2\rho_p}{3\rho_{air}}\right]^2 + 3\left[\dfrac{2\rho_p}{3\rho_{air}}\right]\beta + \dfrac{9}{2}\beta^2\left[1 + \beta + \dfrac{\beta^2}{2}\right]}$$

where ρ_p is the aerosol particle density and $\rho_{air} \approx .0012\ g/cm^3$ is the density of air. If we express particle diameter in μm, particle density in g/cm^3 and frequency f in hertz then the absorption coefficient α_a^ν due to viscous losses in units of m^2/g is

$$\alpha_a^\nu = \frac{\dfrac{5.3}{\rho_p}\left[\dfrac{1}{D^2} + \dfrac{f^{1/2}}{4370D}\right]}{1 + \dfrac{23.6}{D\rho_p f^{1/2}} + \dfrac{278}{D^2\rho_p^2 f}\left[1 + \dfrac{4370}{Df^{1/2}} + \dfrac{9550000}{D^2 f}\right]}$$

with contourplots of α_a^ν appearing in Figures 3 and 4.

The absorption coefficient concentration product due to irreversible heat transfer losses can be written [3,4]

$$\alpha_a^\kappa C = \frac{2\pi\kappa Dn}{U_S}\left(\gamma - 1\right)\left[1 + \frac{1}{\beta}\right]\mu_\kappa$$

2

where $\kappa \approx 0.187$ cm^2/s is the thermal diffusivity of air, $\gamma \approx 1.4$ is the constant pressure over constant volume heat capacity ratio for air which is approximately that of a diatomic molecule and

$$\mu_\kappa = \frac{\left(\dfrac{2\rho_p}{3\rho_{air}}\right)^2}{\left[\dfrac{2\rho_p}{3\rho_{air}}\right]^2 + 3\left[\dfrac{2\rho_p}{3\rho_{air}}\right]\Theta + \dfrac{9}{2}\Theta^2\left[1 + \Theta + \dfrac{\Theta^2}{2}\right]}$$

where

$$\Theta = \frac{(8\kappa/\omega)^{1/2}}{D}.$$

The absorption coefficient in units of m^2/g due to irreversible heat transfer losses becomes

$$\alpha_a^\kappa = \frac{\dfrac{1.76}{\rho_p}\left[\dfrac{1}{D^2} + \dfrac{f^{1/2}}{4370D}\right]}{1 + \dfrac{26.3}{D\rho_p f^{1/2}} + \dfrac{347}{D^2\rho_p^2 f}\left[1 + \dfrac{4880}{Df^{1/2}} + \dfrac{11007200}{D^2 f}\right]}$$

where again particle diameter is expressed in microns, density in g/cm^3, and frequency in hertz. Contourplots of α_a^κ are presented in Figures 5 and 6.

Discussion

Total aerosol absorption acoustic cross sections per volume (square meters per cubic centimeter) due to combined viscous and irreversible heat transfer losses are plotted in Figures 7 and 8 in units of square meters per cubic centimeter of aerosol at an aerosol particle density of 5g/cc. In Figures 9 and 10 the cross sections per mass (square meters per gram) are similarly plotted. Optimum diameter regions producing maximum contour levels for the sound absorption cross sections per volume or per mass are clearly indicated. For example, the optimum diameter for a $\rho = 5$ g/cc density particle attenuating 7000 Hz acoustic radiation would be about 1.5 μm and the absorption coefficient is about 2 m^2/cc. At lower frequencies the optimum diameters are larger and the absorption cross sections are smaller. For example, the optimum diameter for attenuating 700 Hz sound is about 4.5 μm and the absorption coefficient is about 0.2 m^2/cc. Figures 11 and 12 for unit density particles can be compared to Figures 9 and 10 for 5 g/cc density particles. Although optimum diameters for the unit density particles are substantially greater than the optimum diameters for the 5 g/cc particles, the absorption cross section per mass has not changed very much. Because we may roughly estimate the cross section per volume as the particle density multiplied by the cross section per mass, we can expect that the cross section per volume of the 5 g/cc particles will be about 5 times greater than that of the unit density particles. Figures 13 and 14 show the sound absorption cross sections per volume and per mass as a function of particle diameter and density for 100 Hz sound. Similarly Figures 15

3

and 16 show it for 1000 Hz and Figures 17 and 18 for 10000 Hz frequencies. Optimum diameters are indicated in the plots of cross section per volume with increases in cross section per volume to be expected with increasing particle density assuming the necessary adjustments in diameter are made. On the other hand, there is a ridge of high cross section per mass in particle density-diameter space so that increasing particle density will not increase cross section per mass as long as optimum diameters are chosen. Optimum diameters can be seen to increase with decreasing density along the ridge. Again the contour levels for absorption coefficients are seen to be approximately proportional to the frequencies.

Comparing the levels of audible sound attenuation by atmospheric gases plus water vapor as indicated in the first two figures with the levels of attenuation achievable with an aerosol, we find that aerosol absorption of sound can greatly exceed that of the intervening air.

Conclusion

Aerosol acoustic absorption cross sections per aerosol volume and mass have been contourplotted by taking surfaces defined by constant values of one of the three variables - particle density, diameter and frequency of sound; while the remaining two variables define the abscissa and ordinate of the contourplot. Regions of high acoustic cross section per volume and mass have been shown and optimum ranges for the independent variables have been shown in the contourplots. We have found that the higher audible frequencies are absorbed by an aerosol much more strongly than are the lower audible frequencies roughly in proportion to the frequency. Optimum particle size was found to increase with decreasing acoustic frequencies and higher particle densities were found to increase aerosol absorption per mass but not per volume at the optimum diameter Finally, aerosol absorption can be made much greater than atmospheric absorption of audible sound.
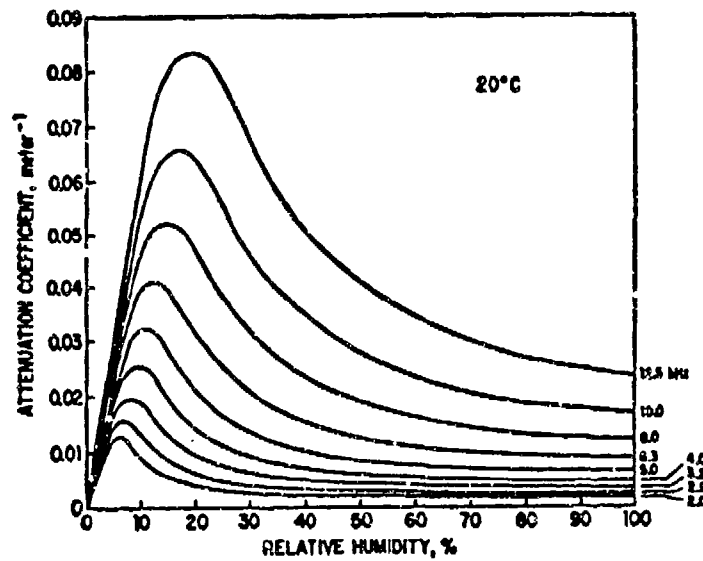
4

Figure 1. Values of the total attenuation coefficient versus percent relative humidity for air at STP for frequencies between 2000 and 12500 Hz.
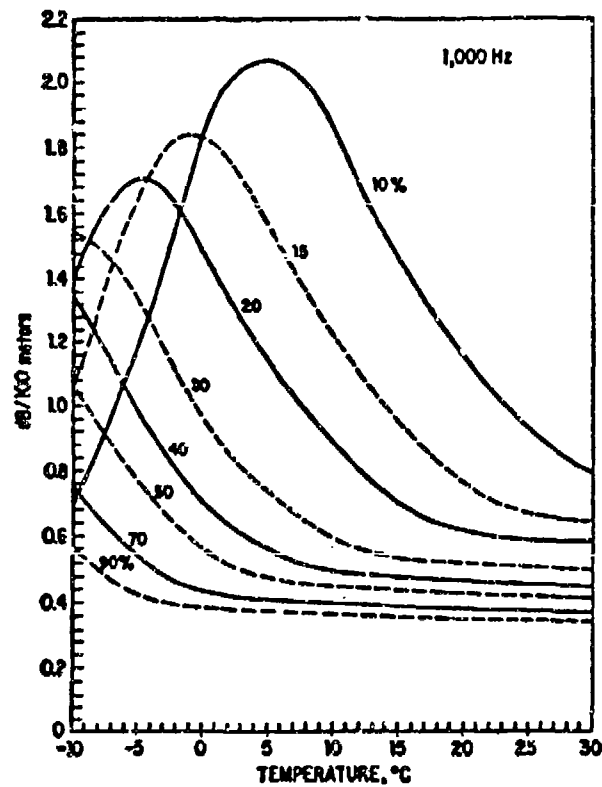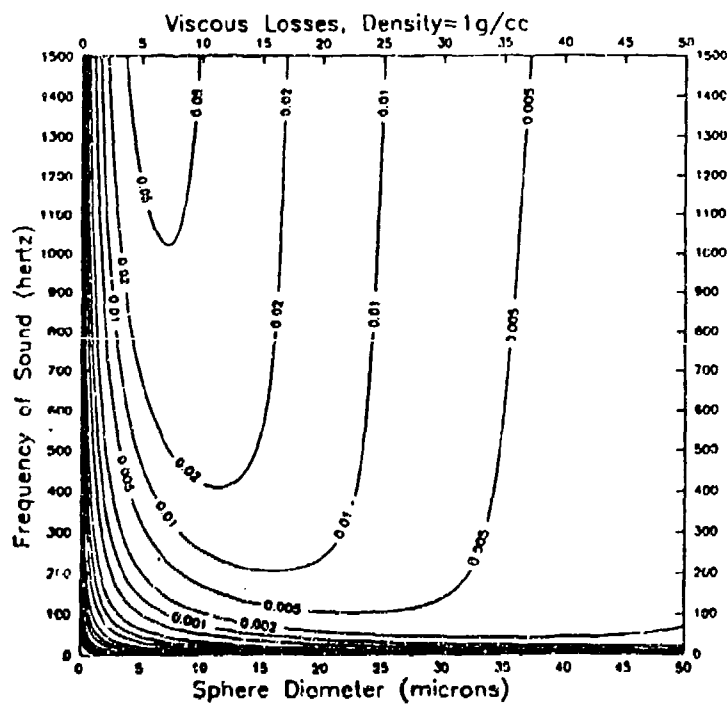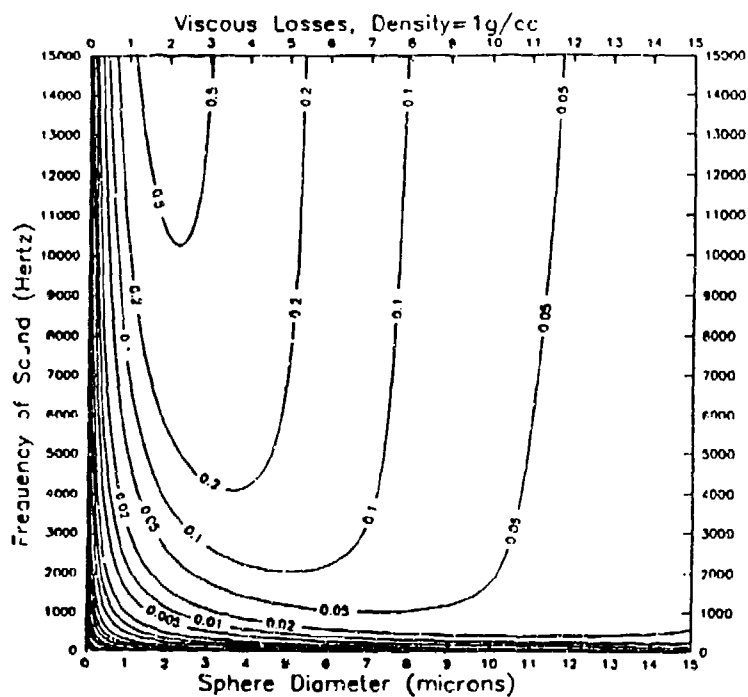

Figure 2. Attenuation of sound in air vs. temperature for various values of relative humidity and 1000 Hz frequency, at atmospheric pressure.
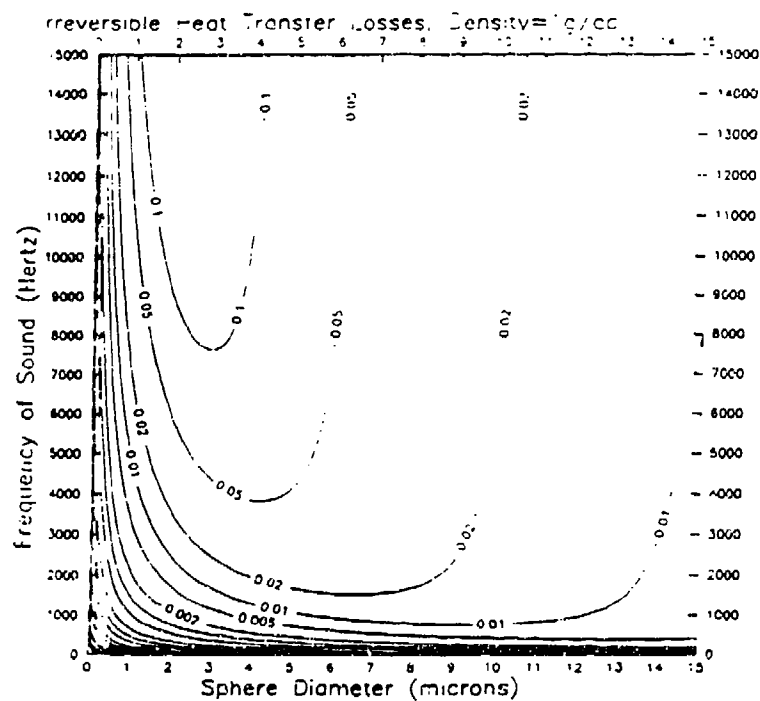
5

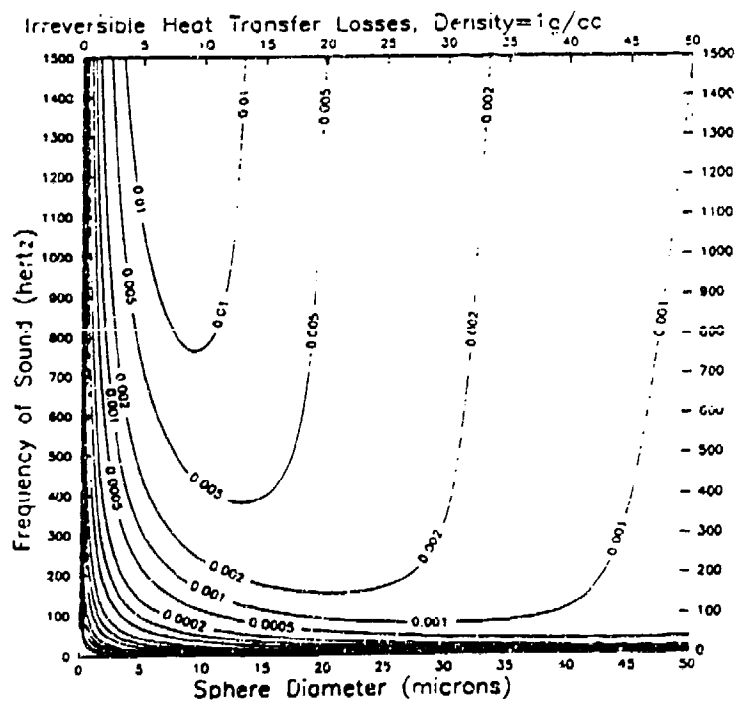**Figure 3.** Aerosol Sound Absorption Coefficient (m*m/g)

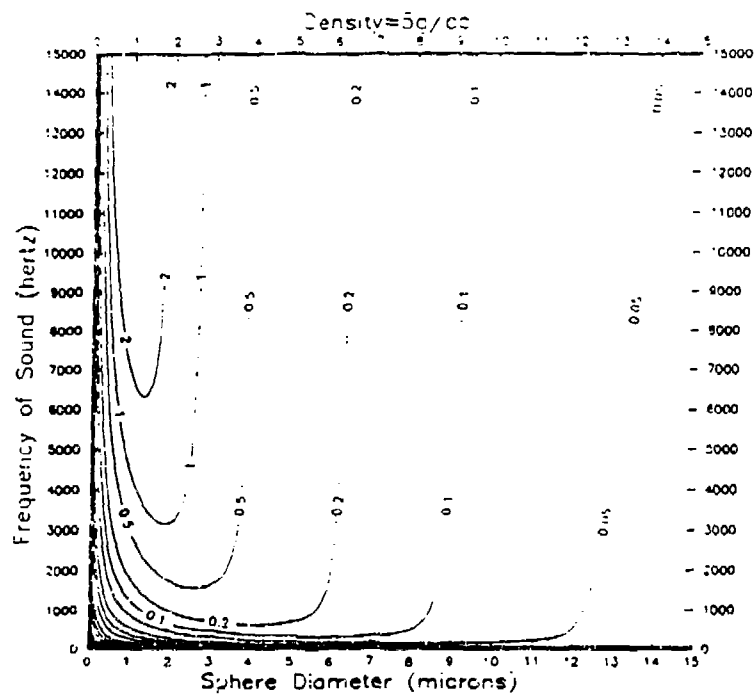**Figure 4.** Aerosol Sound Absorption Coefficient (m*m/g)
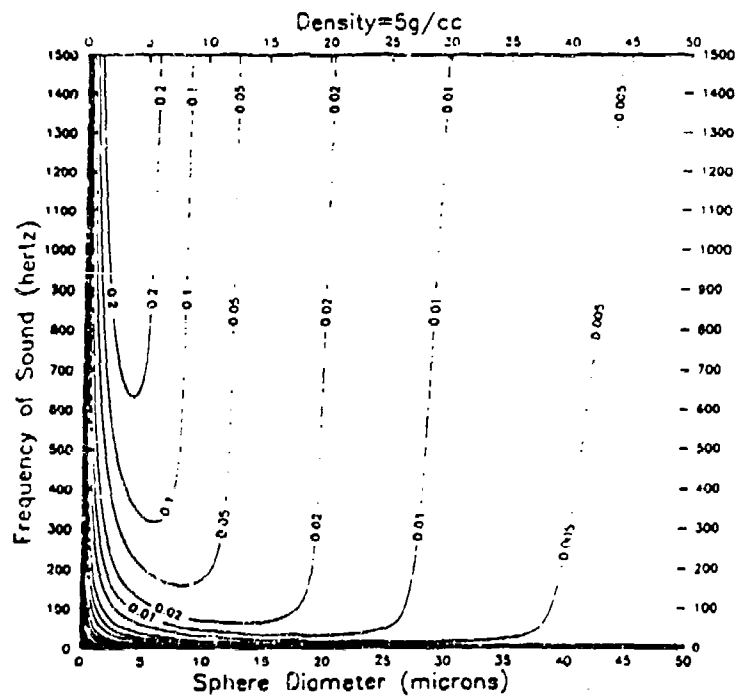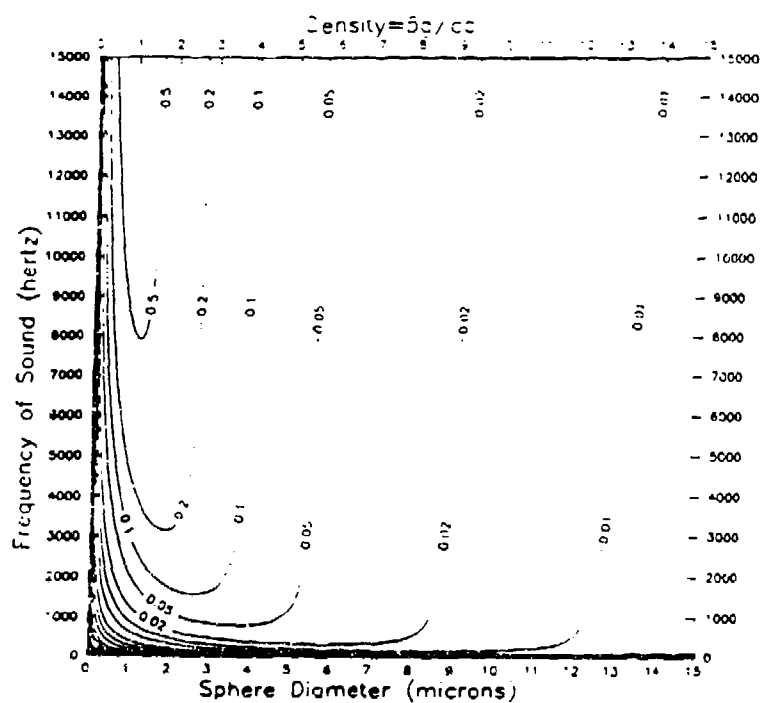
6

Figure 5. Aerosol Sound Absorption Coefficient (m*m/g)

Figure 6. Aerosol Sound Absorption Coefficient (m*m/g)

7

Figure 7. Aerosol Sound Absorption Coefficient (m*m/cc)

Figure 8. Aerosol Sound Absorption Coefficient (m*m/cc)
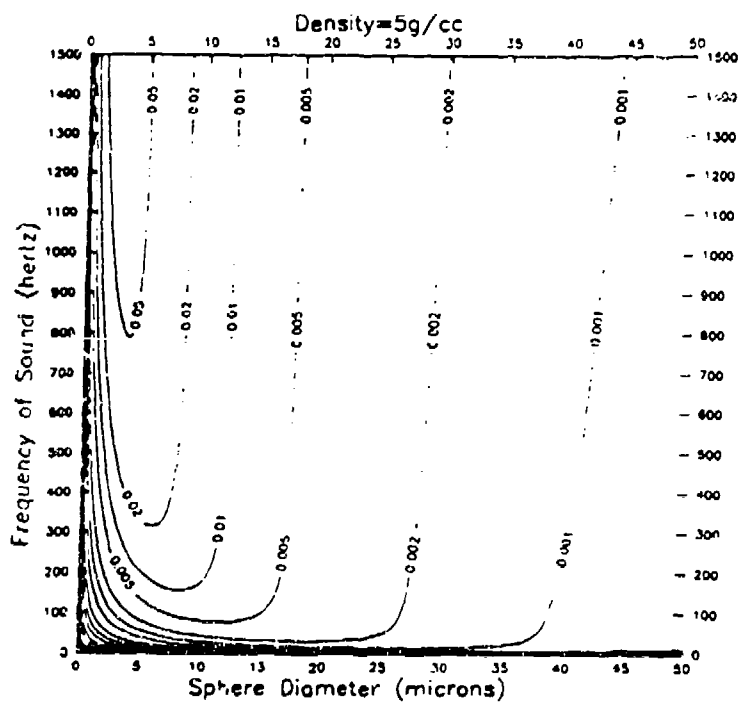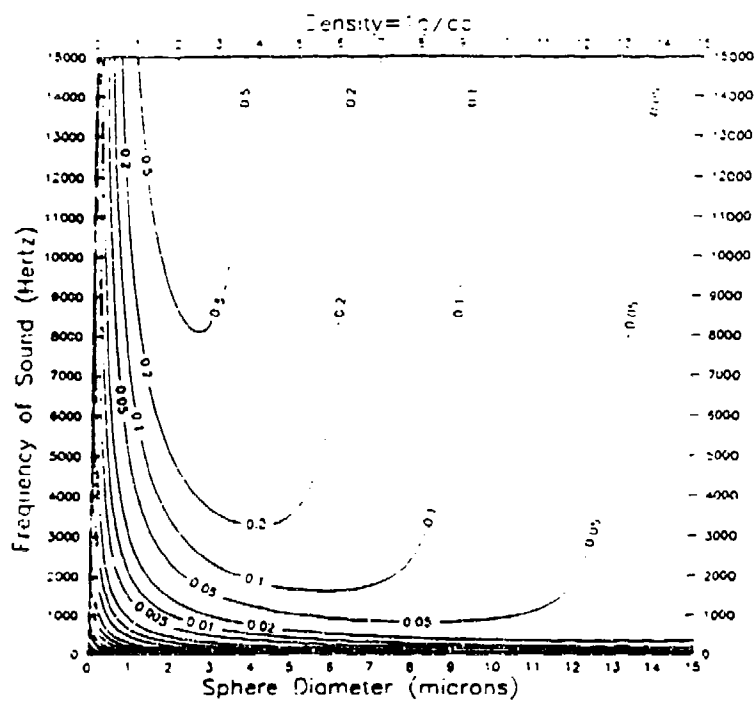
8

Figure 9. Aerosol Absorption Coefficient (m*m/g)

Figure 10. Aerosol Absorption Coefficient (m*m/g)
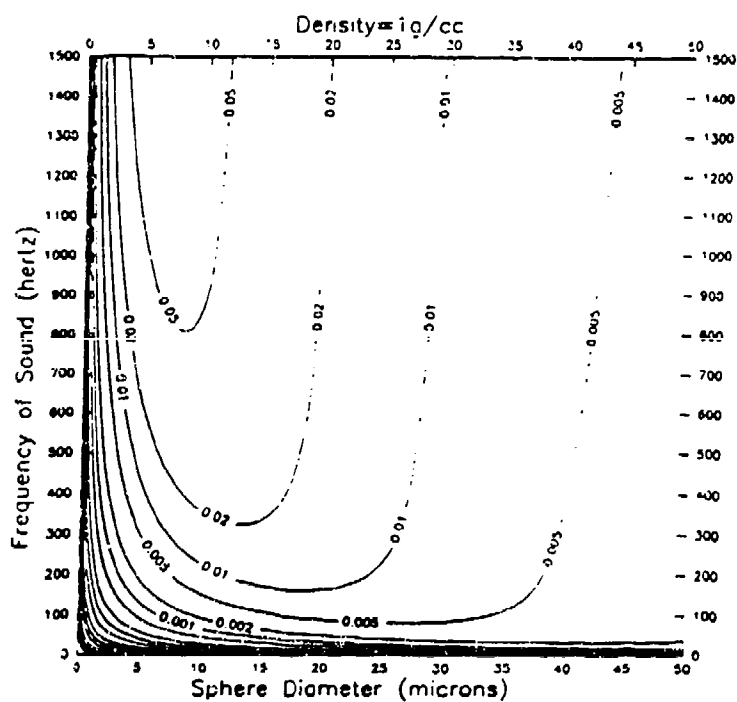
9

Figure 11. Aerosol Sound Absorption Coefficient (m*m/g)
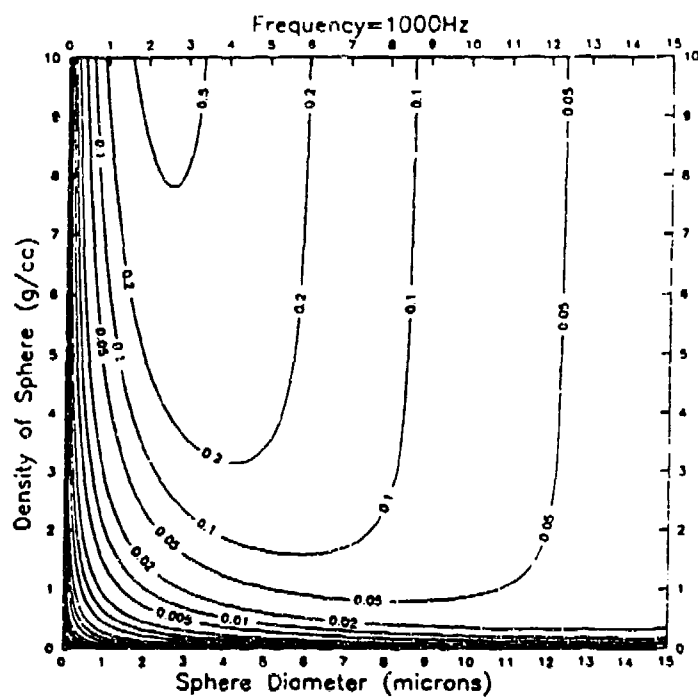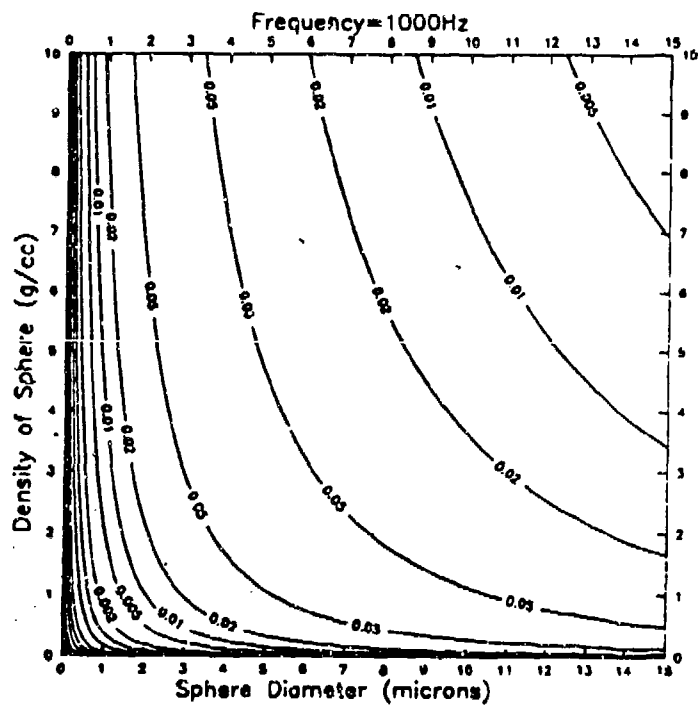

Figure 12. Aerosol Sound Absorption Coefficient (m*m/g)

10

Figure 13. Aerosol Sound Absorption Coefficient (m*m/cc)

Figure 14. Aerosol Sound Absorption Coefficient (m*m/g)

11

Figure 15. Aerosol Sound Absorption Coefficient (m*m/cc)

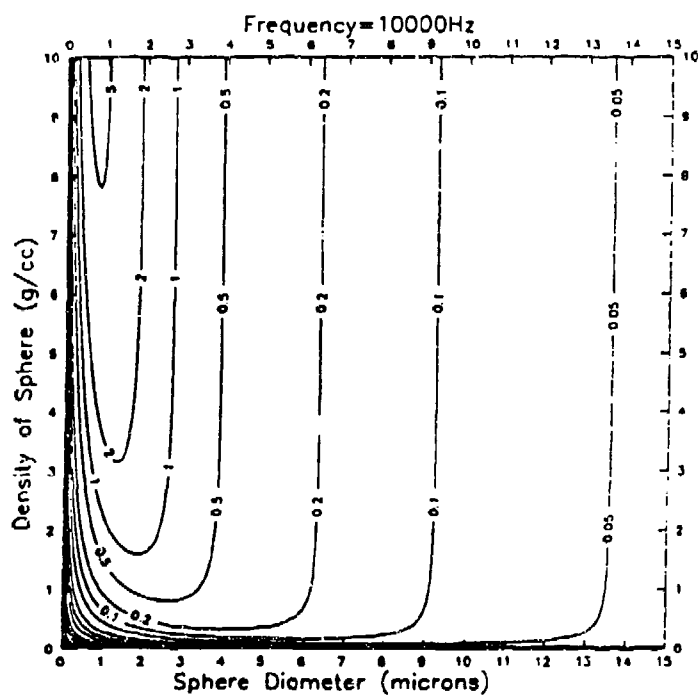Figure 16. Aerosol Sound Absorption Coefficient (m*m/g)

12

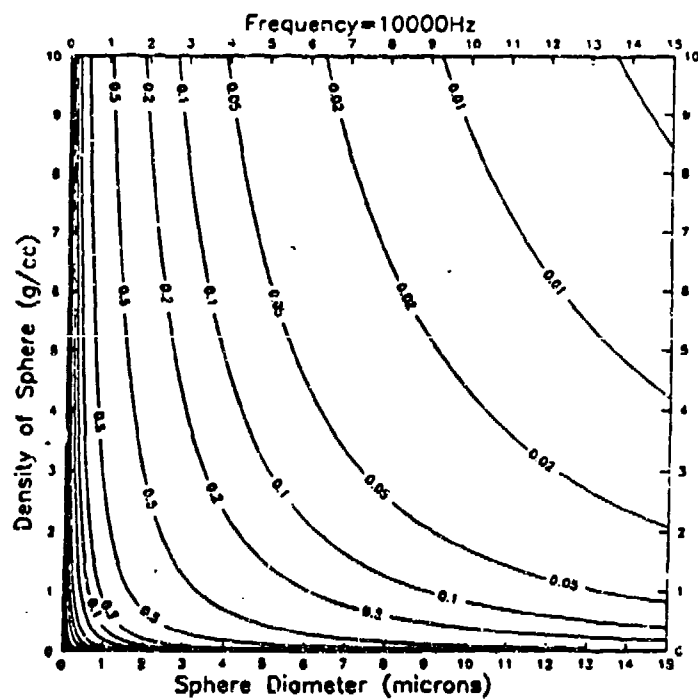Figure 17. Aerosol Sound Absorption Coefficient (m*m/cc)

Figure 18. Aerosol Sound Absorption Coefficient (m*m/g)

13

Blank

LITERATURE CITED

1. AIP Handbook, Third Edition, McGraw-Hill, N.Y. (1972)

2. N.A. Fuchs, "The Mechanics of Aerosols", Pergamon Press, Macmillan Company, N.Y. (1964)

3. P. Epstein and R. Carhart, J. Acoust. Soc. Amer., **25**, 553 (1953)

4. J. Zinc and L. Delsasso, J. Acoust. Soc. Amer., **30**, 765 (1958)